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NAVAL POSTGRADUATE SCHOOL

Monterey, California

APPLICATION OF SATELLITE CLOUD BRIGHTNESS DATA FOR LARGE-SCALE TROPICAL ANALYSIS: A CORRELATION STUDY OF BRIGHTNESS AND 200-MB DIVERGENCE

C.-P. Chang

August 1974

Preliminary Report for Period July 1973 - July 1974

Approved for public release; distribution unlimited.

Prepared for:
National Environmental Satellite Service
National Oceanic and Atmospheric Administration
Washington, D. C. 20023

NAVAL POSTGRADUATE SCHOOL
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This is a preliminary analysis of digitized satellite cloud brightness data that will be used in developing a model for large-scale analysis over data-void tropical areas, which is based on Wallace's (1971) postulation that such data may be used to estimate vertical motion in the tropics.

The relationship between satellite cloud brightness and large-scale 200 mb divergence on $5^{o} \times 5^{o}$ grids in the tropical western North Pacific is

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examined from several angles. Correlation coefficients between the two fields are computed on a daily basis for the region of study and at each grid point for 8-month time series. The coefficients are mostly low although a positive correlation is generally indicated. The low correlation may be due to the quality of the available data, especially for the divergence which is kinematically computed from analyzed winds. Spectrum analysis is also performed to determine dominant synoptic time scales for both parameters in the period of study. Two common period bands, one centered ~ 10 days and the other ~ 5 days, are found. Cross-spectra between the two parameters indicate that their phase differences are small (< 1/4 cycle) for both bands, but the coherence squares are somewhat lower than those found previously by Wallace for the 4- to 5-day waves using direct radiosonde data. Horizontal structures of both parameters, determined from inter-longitude cross-spectra in the two bands, suggest that the brightness is much more organized than divergence, but the two fields resemble each other whenever an organized pattern in divergence can be found.

The results of this study lend some support to Wallace's postulation, but also indicate some problems for using the present data. It is anticipated that the correspondence with the actual divergence field will be greatly improved if satellite infrared data is incorporated into the brightness data.

SUMMARY

This is a preliminary analysis of digitized satellite cloud brightness data that will be used in developing a model for large-scale analysis over data-void tropical areas, which is based on Wallace's (1971) postulations that such data may be used to estimate vertical motion in the tropics.

The relationship between satellite cloud brightness and large-scale 200-mb divergence on $5^{\circ} \times 5^{\circ}$ grids in the tropical western North Pacific is examined from several angles. Correlation coefficients between the two fields are computed on a daily basis for the region of study and at each grid point for 8-month time series. The coefficients are mostly low although a positive correlation is generally indicated. The low correlation may be due to the quality of the available data, especially for the divergence which is kinematically computed from analyzed winds. Spectrum analysis is also performed to determine dominant synoptic time scales for both parameters in the period of study. Two common period bands, one centered $\sim$ 10 days and the other $\sim$ 5 days, are found. Cross-spectra between the two parameters indicate that their phase differences are small (< 1/4 cycle) for both bands, but the coherence squares are somewhat lower than those found previously by Wallace for the 4- to 5-day waves using direct radiosonde data. Horizontal structures of both parameters, determined from inter-longitude cross-spectra in the two bands, suggest that the brightness is much more organized than divergence, but the two fields resemble each other whenever an organized pattern in divergence can be found.

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1. Introduction

Satellite photographs of tropical regions have revealed that much of the tropical cloudiness is in the form of large, connected masses of very bright clouds. These masses are composed of many individual cumulus clouds, whose extensive cirrus canopies with a horizontal scale of several hundred km or larger account for most of their brightness. These large, bright cloud masses, or "cloud clusters" as they are now called, have received considerable attention in recent years. Chang (1970) and Wallace (1970, 1971), using time-longitude series of satellite photographs, found that many cloud clusters over the tropical Pacific are well organized and have characteristics resembling those of synoptic-scale westward propagating wave disturbances. Further evidence by Reed and Recker (1971) showed that these propagating cloud clusters in the western North Pacific are linked to synoptic-scale waves in the wind field. Williams and Gray (1973) and Yanai *et al*. (1973) have also deduced the mean properties of these western North Pacific cloud clusters and found several vertical characteristics of the active clusters similar to those found by Reed and Recker (1971) and Nitta (1972) for the wave troughs.

Due to the poor radiosonde coverage over the vast tropical oceans, it is natural to try to utilize the available satellite data as an aid for tropical analysis. Digitized cloud brightness data, acquired by the Advanced Vidicon Camera Systems of the operational satellite system, have been available since 1967. Because of the relationship between the bright cloud clusters and synoptic-scale tropical motions, this data becomes a potential source for such a purpose. In fact, evidences

of relations between the satellite brightness data and other meteorological parameters have been found by several investigators. The correlation between brightness and precipitation has led many attempts to estimate rainfall using satellite brightness [for example, see the review by Martin and Scherer (1973)]. Wallace (1971) also found indication of good correspondence between area-averaged cloud brightness and synoptic-scale vertical motion associated with the 4- to 5-day tropical disturbances in the Kwajalein-Eniwetok-Ponape triangle of the Marshall Islands and the Guam-Truk-Yap triangle farther west. He postulated that it may be possible to obtain an estimate of the vertical motion field over the tropics from the cloud brightness data alone. If this turns out to be the case, the satellite cloud brightness data will certainly be one of the best available indicators of disturbed weather in the tropics.

There are physical reasons to think that brightness data is closely related to the large-scale vertical motion field. The bright cirrus canopies associated with the cloud clusters "are produced by outflow from and remnants of the cumulonimbi. In general, developing and conservative clusters maintain their cumulonimbi from a steady low-level mass convergence; clusters gradually die when their low-level mass convergence is eliminated" (Williams and Gray, 1973). Because of the readily available low-level moisture, the large-scale upward motion provides a favorable environment for the development and existence of the clusters. Furthermore, brighter clouds are usually thicker and therefore may indicate larger amount of latent heat release (Gruber, 1974). Because the magnitude of the latent heating is nearly one order greater than the temperature fluctuations at most levels for large-scale,

convectively-active tropical motions, thermal energy balance requires that the large-scale vertical motion must be approximately proportional to heating (Wallace, 1971; Holton, 1972). Thus one could expect a positive correlation between cloud brightness and large-scale vertical motion by reason of heating alone.

The correspondence between brightness and vertical motion may also be extended to large-scale horizontal divergence at levels where divergence is large, since many observational studies [Wallace (1971), Reed and Recker (1971), Nitta (1972), Williams and Gray (1973), Yanai et al. (1973), Reed and Johnson (1974)] have produced very similar profiles of the vertical motion (or divergence) over tropical areas where convection is active. The same conclusion can also be inferred from the various vertical heating profiles shown by Hayashi (1974) from analyses of tropical output from the general circulation model of the NOAA Geophysical Fluid Dynamics Laboratory at Princeton. In addition, Williams and Gray (1973) have shown a clear in-phase relation between cloud clusters and upper-level divergence in their composite study.

Due to the constraint of available radiosonde network, the study of correlation between brightness and vertical motion by Wallace (1971) is limited to just two "grid points" --the Kwajalein-Eniwetok-Ponape and the Guam-Truk-Yap triangles. It will be quite significant if this positive correlation between brightness and vertical motion or upper-level divergence can be established over a broader area. For example, since deep tropical motions are usually quasi-barotropic, it may be possible to represent the divergence by the brightness data in a one-level vorticity equation to obtain some kind of solution which may resemble the large-scale flow field. This can then be used as a first estimate for

diagnostic purposes over regions where wind observations are sparse or void. The possibility of this kind of application has been increased recently by the available satellite infrared data which, by supplying information of cloud-top temperatures and therefore cloud-top heights, may be used to modify the brightness data and improve the estimate of vertical motion and upper-level divergence fields.

A model of using satellite brightness data based on the foregoing discussion is currently being developed at the Naval Postgraduate School. This study is a preliminary analysis of satellite brightness data which will be used in that model. Our primary purpose is to examine the degree of correspondence between the brightness data and the large-scale vertical motion-divergence field, using the analyzed-wind data from the National Meteorological Center. This data is available at all tropical grid points and thus enables us to examine a large area of tropical western Pacific. In addition to the 4- to 5-day period disturbances studied by Wallace, we will examine the relationship between the two fields from several angles: as functions of space, time, and dominant frequency bands. Correlation and spectrum analyses will be used. The plan of developing the model for using satellite brightness data as an aid to large-scale analysis over data-void tropical regions will also be briefly discussed in the final section.

2. Data sources and periods of study

The general area selected for this study is the tropical western North Pacific, from the equator to 25N and 125E to 175E. There are two reasons for this selection: Firstly, previous spectral wave studies and satellite studies have indicated that this is an area of strong cloud cluster activity. Secondly, this region has eleven rawinsonde stations including the Caroline and Marshall Islands, which makes the analyzed wind data relatively more reliable compared to other areas in the tropics. Fig. 1 shows the region and the rawinsonde network.

The digitized cloud brightness and upper-level wind data used in this study were provided by the National Center for Atmospheric Research (NCAR). The cloud brightness data, acquired by NCAR from the National Environmental Satellite Service (NESS), are digitized values averaged for $5^{\circ} \times 5^{\circ}$ latitude-longitude squares. Upper-level component winds at the 700, 500, 300, 250 and 200 mb levels were acquired by NCAR from the National Meteorological Center tropical grid analyses. These winds are given at grid points approximately coinciding with those for the brightness data, and are the result of analyses based on all available rawinsondes, aircraft observations and a few winds deduced from cloud drift as seen from satellite photographs. NCAR also provided rawinsonde observations for the region of study, which were used to obtain analyzed wind fields at low levels. In all cases, the 0000 GMT wind data are considered as being closest to the time of satellite observation.

Two periods have been selected for this study: July 1969 and 19 April - 20 December 1971. The first period, which is just a randomly selected summer month, was first used to compute daily correlations between cloud brightness and vertical motion fields. The second period was selected

when we decided to extend the period of analysis and to resolve correlations for dominant frequency bands. By that time we had learned of the availability of the NOAA-1 satellite infrared data digitized by NESS, which covers approximately a three-month period starting 19 April 1971. We hope that this infrared data can be used at a later date to modify and compare with the present results.

3. Results

3.1 Daily correlations for July 1969

The period of July 1969 contains 23 days of useful brightness data, which were used to compare with the divergence and vertical motion (pressure velocity ω) on a daily basis. The latter fields were computed kinematically on the $5^o \times 5^o$ grids subjected to the boundary constraints, $\omega = 0$ at 1000 mb and 100 mb. The correction necessary to satisfy these constraints is distributed linearly with respect to pressure, resulting in an adjusted divergence and vertical velocity at each level. The validity of such calculations on a $5^o \times 5^o$ grid is undoubtedly questionable, and even more so when one considers that our wind data is already smoothed by the analysis procedure. However, thus far this is the only data available over a broad tropical oceanic area; and, for our purpose, we believe that a crude representation of the vertical motion or divergence field will be adequate to show at least whether the correlations with brightness found by Wallace (1971) on a time series basis at two "grid points" can be extended to a larger area on a daily basis. Furthermore, the computed divergence profiles in areas of high brightness usually show a deep layer of convergence capped with a relatively shallow layer of divergence, which are generally in good agreement with the results found by Wallace (1971), Reed and Recker (1971), Williams and Gray (1973) and others, thus lending some confidence to the calculations.

The daily correlation coefficients of brightness vs vertical velocity and divergence were computed at all levels. Generally, the 300- to 400-mb vertical velocities and the 200-mb divergence show better correlations with brightness as compared to other levels. This is somewhat expected because previous observational studies all found that the non-divergent

level is $\sim$ 300- to 400-mb, while the 200 mb level is the outflow level with maximum divergence. Table 1 lists the daily correlation coefficients for the 300-mb vertical velocity (ω_{300}) and 200-mb divergence (div_{200}). The sample size is 66, which gives us a value of 0.24 for the 95% significant level and 0.20 for the 90% significant level, using Panofsky and Brier's (1965) formula. Out of the 23 days of useful data, 14 days show a significant correlation at 90% level or better between brightness and ω_{300} , with 13 days negative and 1 day positive. These correlation coefficients are quite low as compared to that (inferred from coherence square) found by Wallace (1971) for the 4- to 5-day waves at the Kwajalein-Eniwetok-Ponape triangle, although they do indicate a tendency of in-phase relationship between the two parameters on a daily basis. It is possible that the lower correlation is partly due to the quality of our computed divergence data which is based on analyzed winds, but our results do suggest that the correspondence between the two fields is far from perfect. In column 2 of Table 1 the correlation coefficient between ω_{300} and a smoothed brightness data is also listed. Here the smoothing procedure is done by a simple 5-point, centrally-weighted spatial averaging in order to reduce the effect of isolated high or low spots that appear occasionally. However, this averaging turned out to be of little use. Although most of the correlations are slightly higher, they are not too different from those for the original brightness.

The correlation of brightness vs div_{200} , as shown in Table 1, seems quite similar to that for ω_{300} although many coefficients are slightly lower. This similarity in correlation with brightness is somewhat expected from the previous observation that the vertical profile of vertical velocity (or divergence) remains approximately the same in the regions of strong cloud-cluster activities.

In addition to the correlation calculations, we also visually compared the plotted contour patterns of the brightness with those for the ω_{300} and div_{200} fields. This subjective examination reveals that the area enclosed by 10^{o}N, 20^{o}N, 130^{o}E and 155^{o}E generally shows better correspondences between the different parameters. In fact, the eastern portion of the region (160^{o}E - 175^{o}E) possesses comparatively few organized brightness patterns in the contoured diagrams and usually exhibits a widespread area of zero or low brightness. This increase in organization and intensity of brightness toward the western portion may be a reflection of the westward intensification of wave disturbances in this region found by Chang et al. (1970) and Reed and Recker (1971). Chang (1970) and Sikdar et al. (1972) also noted a marked geographical variation in cloud activity over the Pacific.

3.2 Correlations for 1971

Because the July 1969 correlation results are similar for ω_{300} and div_{200}, we decided to use the horizontal divergence only for correlation with the cloud brightness for 1971. The divergence is derived directly from the horizontal wind components at all levels without any adjustment by vertical boundary constraints. The 200-mb level again turns out to be the maximum divergence level for almost all the days in this period, so only results using div_{200} are presented here and in 3.3.

Table 2 lists the daily correlation coefficients of brightness vs div_{200} for a four-month summer-autumn period, namely July-October 1971. Among the 119 days with useful data, 45 days show positive correlation at the 90% level or better, while 4 days show negative correlation.

These results are similar to those of July 1969 and also provide a weak indication of positive correlation between the two fields on a daily basis.[1]

The correlation coefficients between the 8-month (19 April - 20 December 1971) time series of each parameter were also computed at all grid points in order to examine the spatial distribution of the correlations. The results are listed in Table 3. Among the 66 grid points for the entire region, 25 points show positive correlation at the 90% level or better vs 3 points with negative correlation. This ratio is compatible with the daily computations. In fact, all three negative points are in the southeast corner of the region, and most interior points show positive correlations. This situation is somewhat similar to the results of our visual inspection of the July 1969 data mentioned earlier. It thus seems to us that if a region bounded by 5N, 20N, 130E and 160E is chosen, the daily correlations would be much improved.

3.3 Spectrum analysis for 1971

The correlation coefficients between brightness and div_{200} listed in Tables 1-3 are quite low as compared with the coherence for the 4- to 5-day waves found by Wallace (1971) in the Kwajalein-Eniwetok-Ponape triangle. Therefore, it may be worthwhile to do a spectrum analysis of our data and compare the results with Wallace's. In addition, the existence and importance of synoptic-scale disturbances in the tropics have been well recognized. It is reasonable to expect

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[1]However, because of the many uncertainties in the computed divergence data, the percentage of positive correlation in Tables 1-2 should not be viewed as equivalent to the probability of finding a positive correlation between brightness and the actual div_{200} on a given day.

that the variations in both the divergence and the brightness fields are highly influenced by these disturbances, and these variations may be characterized by certain dominant time scales associated with the synoptic-scale disturbances (which may or may not be related to the easterly waves). However, it is unclear whether our previous correlation results are mostly due to the very large scale controls (such as monsoonal circulations, location of ITCZ, etc.) or the synoptic disturbances. If we want to try to use the brightness data to represent divergence or vertical motion on a daily basis, it is necessary that the characteristic behavior of the two parameters resemble each other in these synoptic time scales. For these reasons, spectrum and cross-spectrum analyses are performed for the 19 April - 20 December 1974 time series of both parameters at all 66 grid points within the region of study.

Before the spectral results are presented, it is useful to briefly discuss our aim as compared to those of other spectrum studies of satellite brightness data attempted previously by tropical meteorologists. There have been a number of such studies (Tanaka and Ryuguji, 1971, 1973; Murakami and Ho, 1972; Sikdar _et al._, 1972, and others) carried out, primarily for the purpose of identifying tropical wave disturbances. Although some have yielded interesting results, Wallace and L. Chang (1972) have suggested that the number of spectral peaks found by these studies may be so numerous that it appears rather difficult to extract useful information from the results. They have also pointed out that the time spectra of the present brightness data are highly variable in both space and time, and even neighboring grid points may exhibit quite different spectral characteristics. However,

our primary purpose in using spectrum analysis is not to identify general wave scales, but rather to determine how much the brightness data resembles the divergence when both parameters are decomposed into various time scales which are of synoptic interst in our period of study.

All the 8-month time series are reduced to a length of 198 days after the application of a high-pass filter, which does not have much effect for periods < 20 days. (The response at the 20-day period is 97%.) A lag of 20 days is used for all computations. Figs. 2 and 3 are the power spectra at each grid point for brightness and div_{200}, respectively. After examining these spectra, we found that two frequency ranges, .075 - .125 cycle day^{-1} (or period 8-13.3 days) and .175 - .225 cycle day^{-1} (or 4.4-5.7 days), contain substantial portions of the total variance of most series, hence it is convenient to choose these two bands for comparing the behavior of the two parameters. For simplicity, they shall be subsequently called the 10- and 5-day bands, respectively. Although we are not especially concerned about the location of the spectral peaks, it is nevertheless noteworthy that most of the major peaks do fall into these two bands, and that previous studies by Sikdar et al. (1972), Tanaka and Ryuguji (1973) and Gruber (1974) have all found similar two-band structures in the spectra of tropical brightness data. It thus seems to us that although there is a high variability in the brightness spectra, simple interpretation of a two-band distribution appears to be quite consistent in several studies and should not be overlooked. We also notice that a 3-day spectral peak appears occasionally,but they seldom appear concurrently in both parameters and the fraction of total variance involved is

relatively small in most cases.

The coherence square and phase difference between brightness and div_{200} at each grid point, averaged within each dominant frequency band, are listed in Table 4. The averaging process results in a degree of freedom of ~ 25, which gives a coherence square of 0.17 at the 99% significant level, 0.12 at the 95% level and 0.09 at the 90% level. Only those values significant at the 90% level or better are shown in Table 4. For the 10-day band, 24 grid points have significant coherence squares, and most of them show phase differences from in-phase to $\sim \frac{1}{4}$ cycle between the two parameters. For the 5-day band, 20 points have significant coherence squares. With the exception of 3 points (5N-135E, 20N-145E and 20N-150E), the phase differences also range between in-phase and $\frac{1}{4}$ cycle between the two parameters, but there appears to be more $\frac{1}{4}$ cycle phase differences in this band than in the 10-day band. Comparison of our results for both frequency bands with those of Wallace (1971) for the 4- to 5-day waves showed that, although the two parameters are much more in-phase than out-of-phase, the coherence squares were lower and the phase differences are larger. This is perhaps again due to our use of smoothed, analyzed winds for computing the divergence field.

Another indication of correspondence between the two parameters in the 5- and 10-day bands may be found by comparing the horizontal structures deduced from inter-longitude cross-spectra for both parameters at each latitude. The results are shown in Figs. 4-5. For each latitude the 150E series is used as the base series to cross with other series at the same latitude. Each phase difference is plotted against the longitudinal distance from the base series, and,

unless the points are widely scattered, a best fitting straight line is drawn for each latitude weighted by the significant level of the coherence square associated with each phase value. This technique has been commonly used in spectral wave studies for determining horizontal wavelengths and propagating directions.

For the 10-day band, a westward movement in the brightness data with a "wavelength" of $\sim 50^{\circ}$ can be inferred at all latitudes except the equator, although this simple interpretation seems to be inapplicable in the eastern portion of 10N and 25N, and the easternmost section of 20N. The divergence field is less organized, but a similar structure does appear at 5N, 15N and 20N, the three latitudes where the brightness results are best. In addition, another similarity can be found at 10N. The divergence series are in-phase between 140E-175E and the brightness series are also in-phase between 145E-170E. Both results indicate an east-west orientation and may suggest the presence of an ITCZ with its intensity fluctuating around a period of $\sim$ 10 days.

The structures for the 5-day band seem to be less regular as compared to the 10-day band. Here the brightness is again more organized than the divergence. At least a partial best fitting line can be drawn for brightness at all latitudes, although the "wavelength" range from $\sim 25^{\circ}$ at the northern latitudes to $\sim 50^{\circ}$ at the southern latitudes. Only two organized patterns, at 5N and 20N,can be found for the divergence, but in each case they do remarkably resemble those of their respective brightness fields.

The fact that the brightness data is more organized in Figs. 4-5 reaffirms our belief that its quality is better than that of the divergence, which is expected as mentioned before. Despite the noise present

in our divergence field, whenever an organized pattern in the divergence can be found, it resembles the brightness pattern. This may be viewed as another indication of the correspondence between the two fields.

4. Concluding remarks

In this study we have examined, from several angles, the relationship between the satellite cloud brightness and the divergence-vertical motion field on the $5^{\circ} \times 5^{\circ}$ grid in the tropical western North Pacific. Our results appear to be somewhat mixed. On one hand the correlation coefficients and coherence squares between the two fields are considerably lower than those previously found by Wallace (1971) for the 5-day waves using direct radiosonde data. On the other hand, when the results of various comparisons are integrated, they do form a consistent picture of positive correlation between the two fields. In this regard the present results lend some support to Wallace's contention that it may be possible to estimate the vertical motion or upper-level divergence field over the tropics from digitized satellite brightness data.

Our results are undoubtedly influenced by the quality of divergence data which are deduced from analyzed winds. However, until the observational network in the tropics can be improved, it will be very difficult to obtain better divergence values from wind reports. This is, of course, the precise reason for the attempts to use satellite data. There are also problems in using the brightness data to represent cloud clusters, but the infrared data now available provides a great possibility for improvements. Infrared data supplies information on cloud top temperatures and can be used as an indicator of the vertical extent of cumulus development and therefore the vertical extent of latent heat release. It is thus possible to modify the brightness data by the infrared data and obtain better correlations with the divergence field.

Moreover, since presently there is no reliable direct way to obtain divergence or vertical motion in the data-sparse area of tropics, satellite data remains as one of the best indicators of vertical motion. In this study we have shown that it is possible to deduce organized 200-mb divergence patterns associated with synoptic-scale disturbances from brightness data. There may also be other applications of the satellite data. One possible use, which is currently being investigated at the Naval Postgraduate School, is related to the barotropic and quasi-nondivergent properties of the large-scale tropical flow. As mentioned in the introduction, it may be feasible to describe the tropical flow field at a single level by a barotropic vorticity equation, such as the simple diagnostic model by Holton and Colton (1972) for the 200-mb time mean circulations during the northern summer. Using the observed time mean divergence and mean zonal wind, they successfully reproduced the 200-mb mean motion field by the steady state solution of a linear barotropic vorticity equation with a simple parameterization of the strong damping process. If satellite data can be used to represent horizontal divergence at 200 mb, a similar model may also be developed for a data-void tropical region on a daily basis. Here the mean zonal wind may be represented by climatology and the boundary conditions determined by the data-rich surrounding areas. Since the observational results by Williams and Gray (1973) and many others have shown that the local change of vorticity is rather small compared to other terms in the vorticity equation, a steady-state solution obtained from such a simple model may, to some degree, resemble the actual flow if the strong damping process at 200 mb (Reed and

Recker, 1971; Williams and Gray, 1973) can somehow be represented. If such a model proves to be feasible, it will be very useful for obtaining a first estimate of the 200 mb flow over a data-void region in the tropics.

Table 1. Daily correlation coefficients in hundredths of satellite cloud brightness vs ω_{300} and div_{200} for July 1969. Values shown in parentheses are significant between the 90% and 95% levels; values shown without parentheses are significant at the 95% level or better.

Date	Brightness vs ω_{300}	Smoothed Brightness vs ω_{300}	Brightness vs div_{200}
1 July 1969	-	-	-
2	-	-	-
3	-24	-24	(22)
6	(-21)	(-22)	(20)
8	-	-	-
9	-	-	-
10	-	-	-
11	-	-	-
12	(20)	23	(-21)
13	-	-	-
15	-	-25	-
17	-23	-27	24
19	-23	-23	(21)
20	-24	-24	26
21	(-22)	(-19)	-
22	-30	-33	25
23	-32	-41	33
24	(-22)	-26	(20)
25	-32	-30	31
26	-36	-40	36
27	-60	-62	42
28	-34	-33	27
29	(-19)	-30	-

Table 2. Daily correlation coefficients in hundredths of satellite cloud brightness vs div_{200} for July - October 1971. Values shown in parentheses are significant between the 90% and 95% levels; values shown without parentheses are significant at the 95% level or better. M represents missing data.

Day	July	August	September	October
1	-	M	-	-
2	-	28	-	-
3	(-22)	(22)	-	-
4	-	29	-	26
5	-	28	26	M
6	-	-	-	-
7	(22)	-	31	-
8	28	M	42	33
9	(22)	-31	(20)	-
10	-	-	34	36
11	32	-	-	34
12	38	-	-	(20)
13	30	-	46	M
14	34	-	-	-
15	-	-	44	-
16	-	-	52	-
17	-	-	42	-
18	-	-	(23)	-
19	-	-	-	-
20	-	-	36	-
21	(23)	(20)	25	-
22	40	29	-	-
23	41	-	-	24
24	(21)	-	-	-
25	-	-	(22)	28
26	-29	(23)	(21)	36
27	-	-	-	(20)
28	-	-	(20)	-
29	29	-	(-22)	-
30	39	-	-	-
31	37	-		-

Table 3. Correlation coefficients in hundredths of cloud brightness series vs 200 mb divergence series for 19 April - 20 December 1971. Values shown in parentheses are significant between the 90% and 95% levels; values shown without parentheses are significant at the 95% level or better.

Lat. \ Long.	125E	130E	135E	140E	145E	150E	155E	160E	165E	170E	175E
25N	(10)	-	-	-	-	-	-	-	-	-	-
20N	14	16	-	-	17	17	-	(12)	-	-	-
15N	-	17	(11)	27	25	-	(12)	26	30	20	-
10N	-	-	(10)	(11)	-	(11)	20	19	-	-15	-
5N	-	-	-	(11)	-	(10)	-	-	-	-13	-14
Equator	-	-	(12)	-	17	(10)	-	-	-	-	(12)

Table 4a. Cross-spectra between brightness and 200 mb divergence for the 10-day band for 19 April - 20 December 1971. At each grid point the upper value is coherence square in hundredths and the lower value is phase difference in hundredths of a cycle. Values shown in parentheses are significant between the 90% and 95% levels; values shown without parentheses are significant at the 95% level or better.

Lat. \ Long.	125E	130E	135E	140E	145E	150E	155E	160E	165E	170E	175E
25N	-	-	-	-	-	-	-	-	-	-	-
20N	(11) / -05	(10) / -08	-	-	14 / -13	-	-	(10) / 29	-	-	-
15N	(10) / -04	-	-	(10) / 12	16 / 12	-	-	-	(10) / -01	(10) / 05	-
10N	-	16 / 24	-	13 / 18	12 / -30	(10) / -17	15 / 07	-	-	-	-
5N	-	-	-	24 / 03	15 / 10	(11) / 10	-	(11) / 05	12 / -03	13 / 16	14 / 08
Equator	-	-	14 / 20	20 / 12	15 / 19	-	-	-	-	-	-

Table 4b. Same as Table 4a except for the 5-day band.

Lat. \ Long.	125E	130E	135E	140E	145E	150E	155E	160E	165E	170E	175E
25N	-	-	$\frac{24}{20}$	-	-	-	-	-	-	-	$\frac{(10)}{-04}$
20N	-	$\frac{(10)}{02}$	-	-	$\frac{(11)}{-33}$	$\frac{(11)}{-34}$	$\frac{14}{-20}$	$\frac{(11)}{-22}$	$\frac{(10)}{-18}$	-	-
15N	-	$\frac{16}{-03}$	-	-	-	-	-	$\frac{14}{21}$	-	$\frac{23}{-09}$	$\frac{(10)}{-03}$
10N	-	$\frac{(11)}{13}$	-	-	-	$\frac{19}{03}$	-	-	-	-	$\frac{(10)}{-21}$
5N	-	-	$\frac{(10)}{35}$	-	-	-	-	-	-	-	-
Equator	-	-	$\frac{15}{14}$	$\frac{21}{22}$	$\frac{13}{25}$	$\frac{15}{26}$	-	-	-	-	-

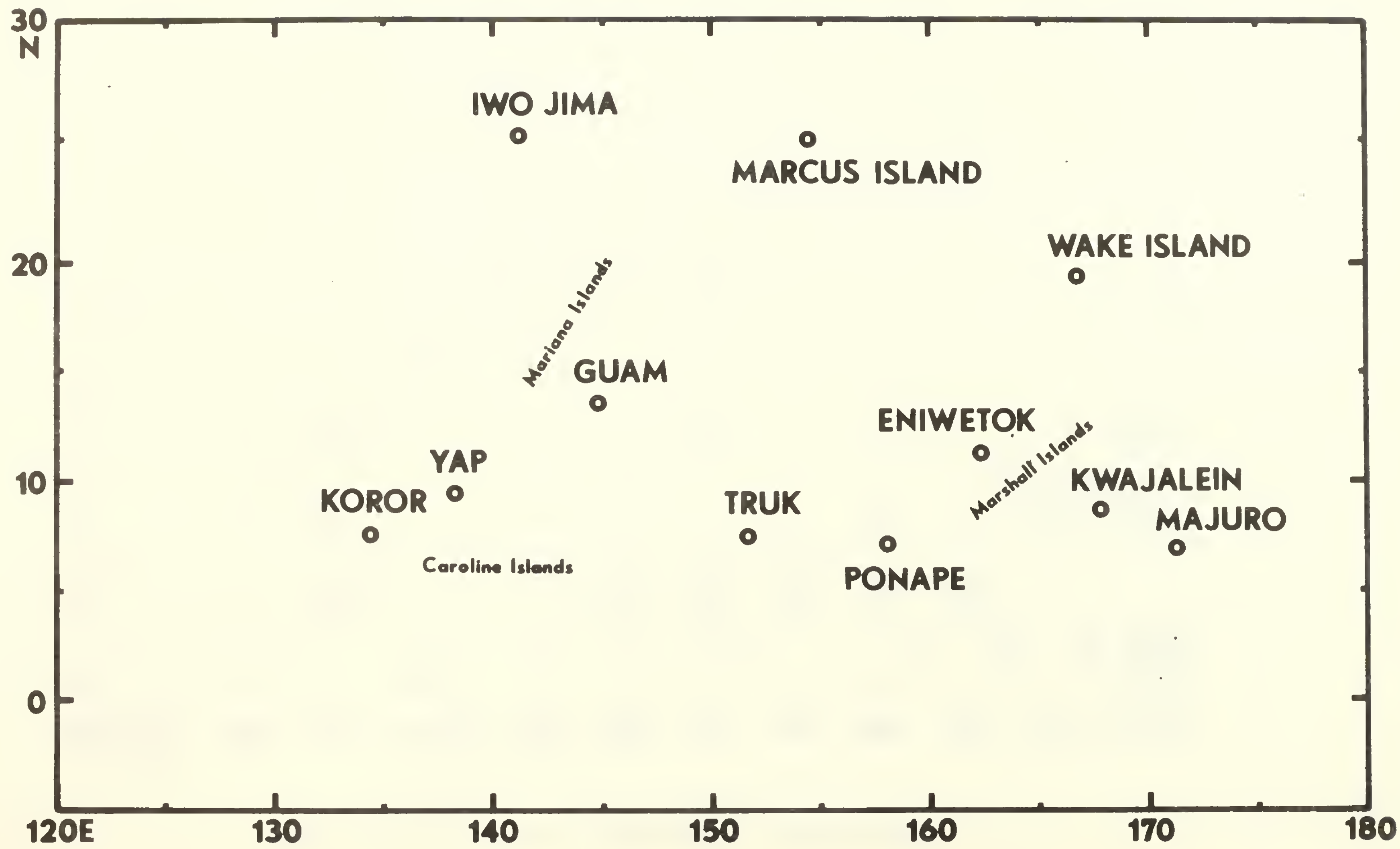

Fig. 1. Region of study and rawinsonde network.

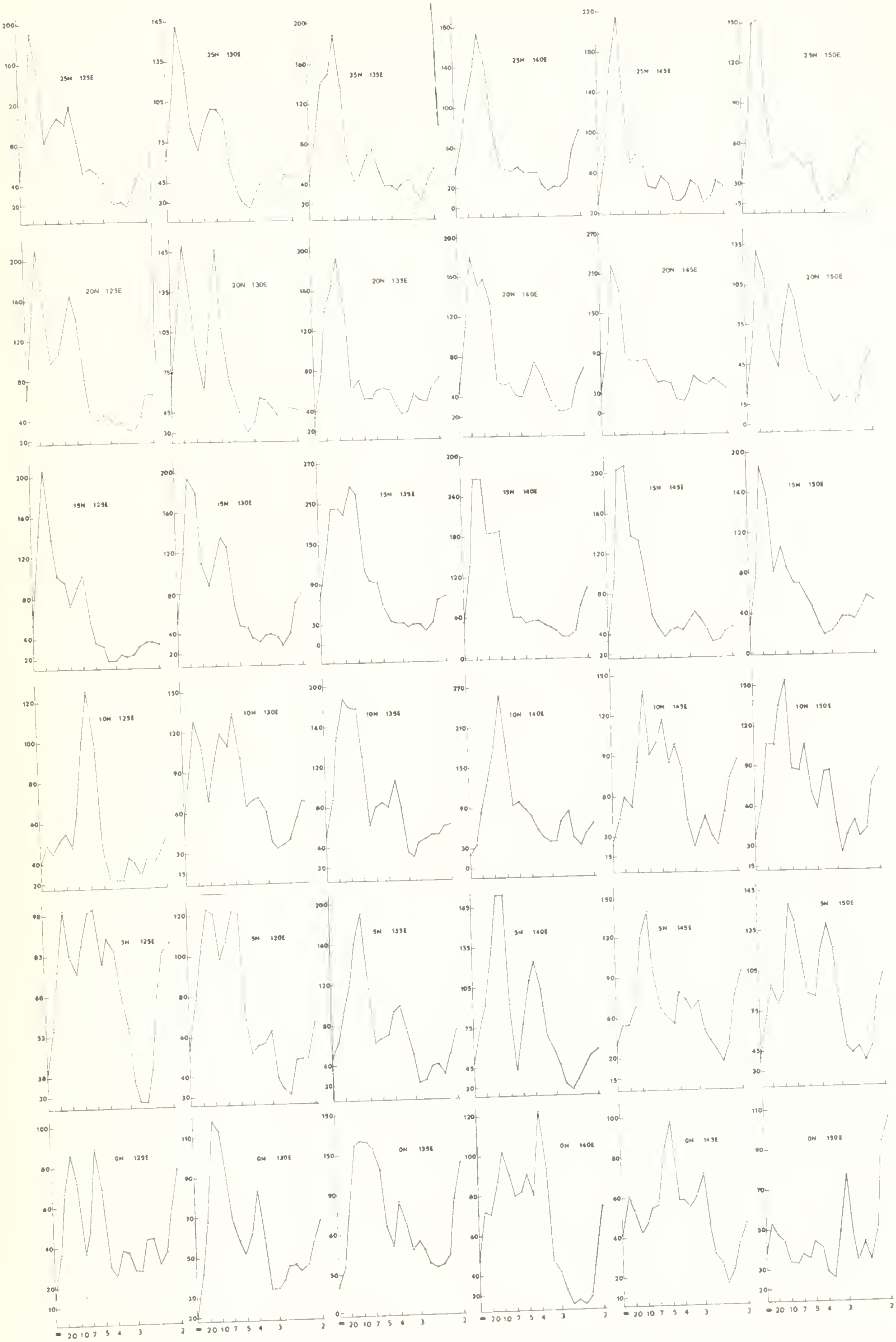

Fig. 2. Power spectra of digitized satellite brightness data at the $5^{o} \times 5^{o}$ grid points. The ordinate is variance per unit frequency interval (B^{2} per $2\pi \times 40^{-1}$ $day^{-1} \times 10^{-2}$, where B is brightness unit with a range from 0 to 10) and the abscissa is period (days).

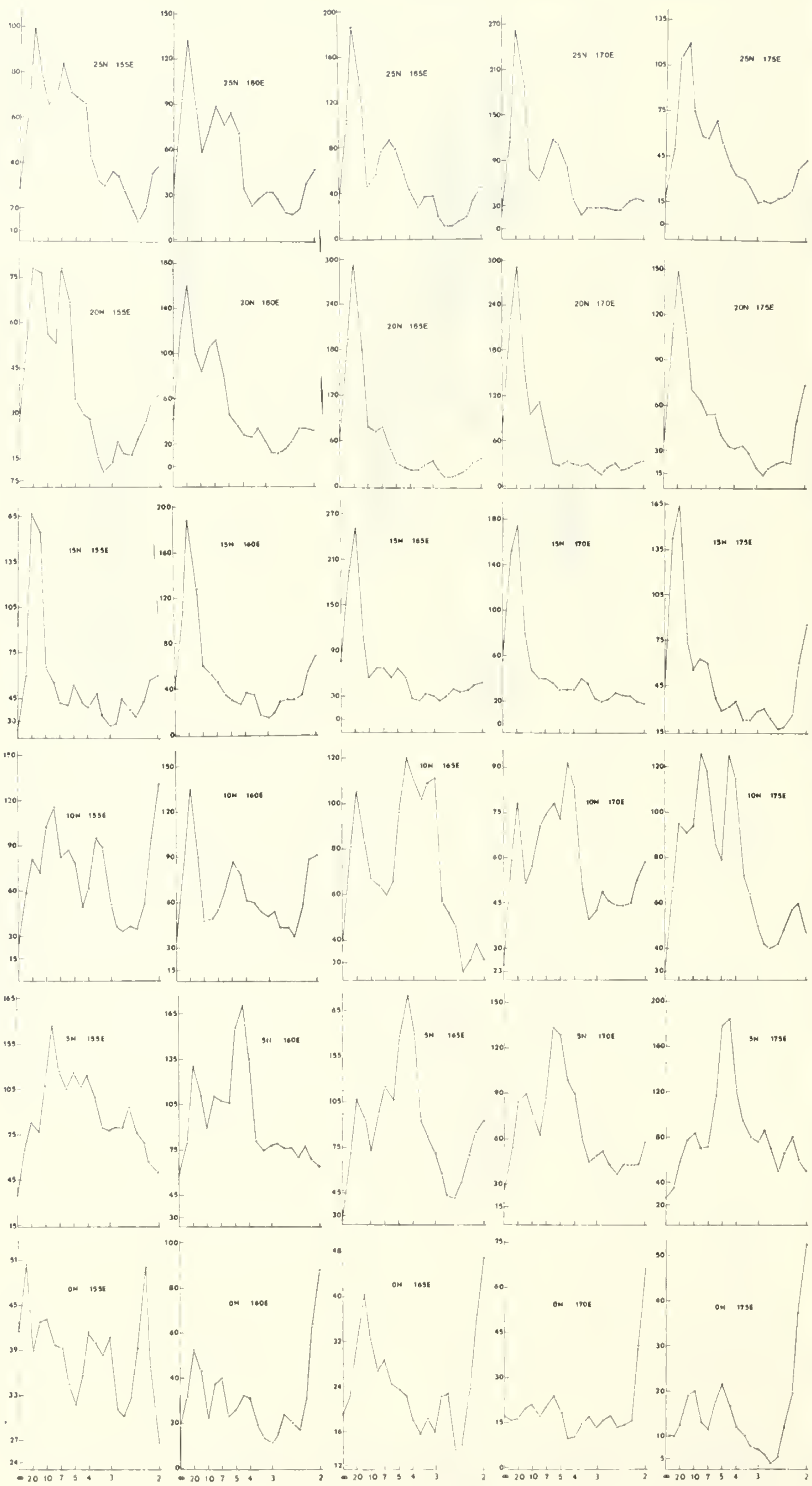

Fig. 2. (continued)

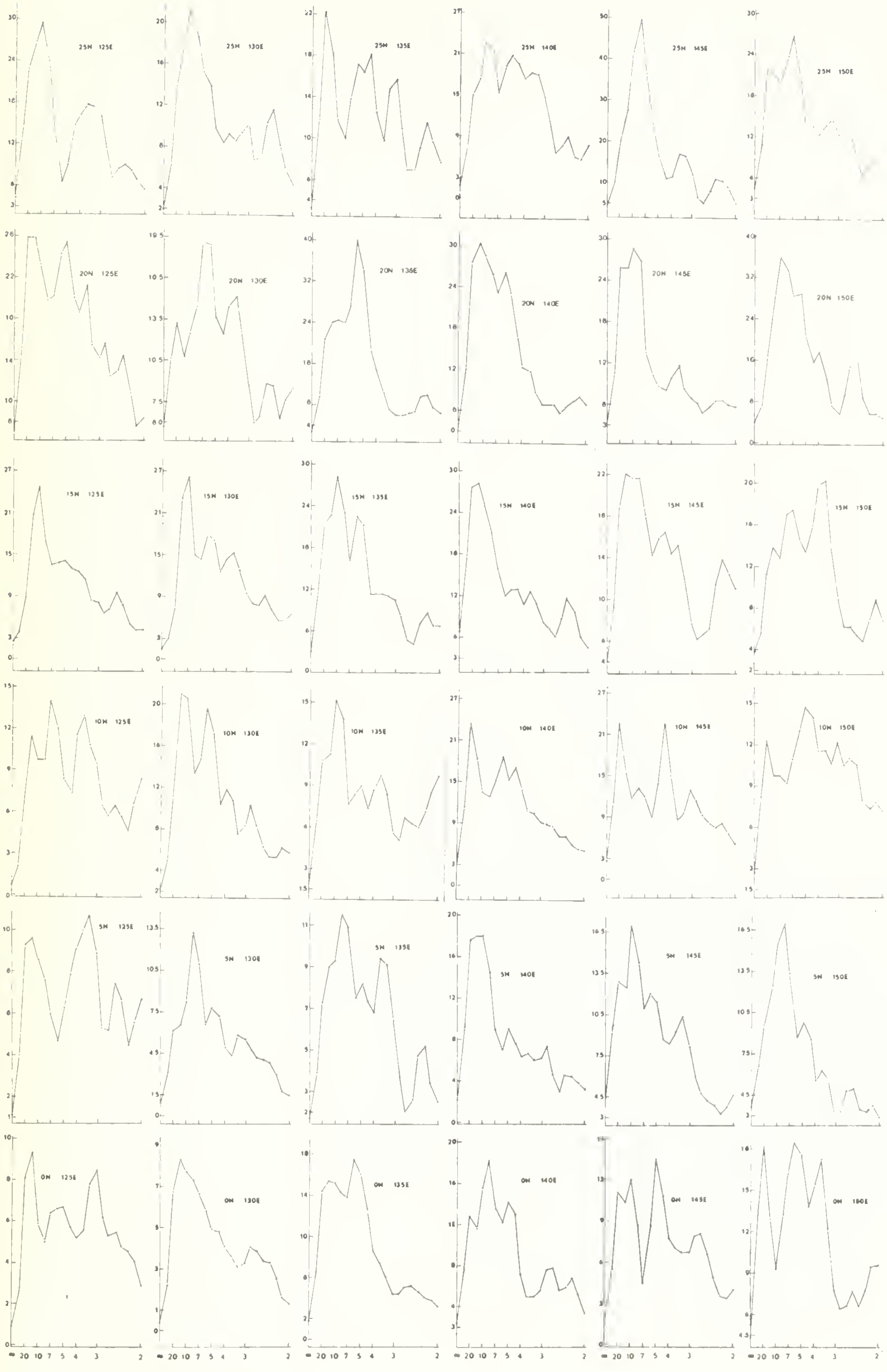

Fig. 3. Same as Fig. 2 except for 200-mb divergence and the unit for the ordinate is sec^{-2} per $2\pi \times 40^{-1}$ $day^{-1} \times 10^{-12}$.

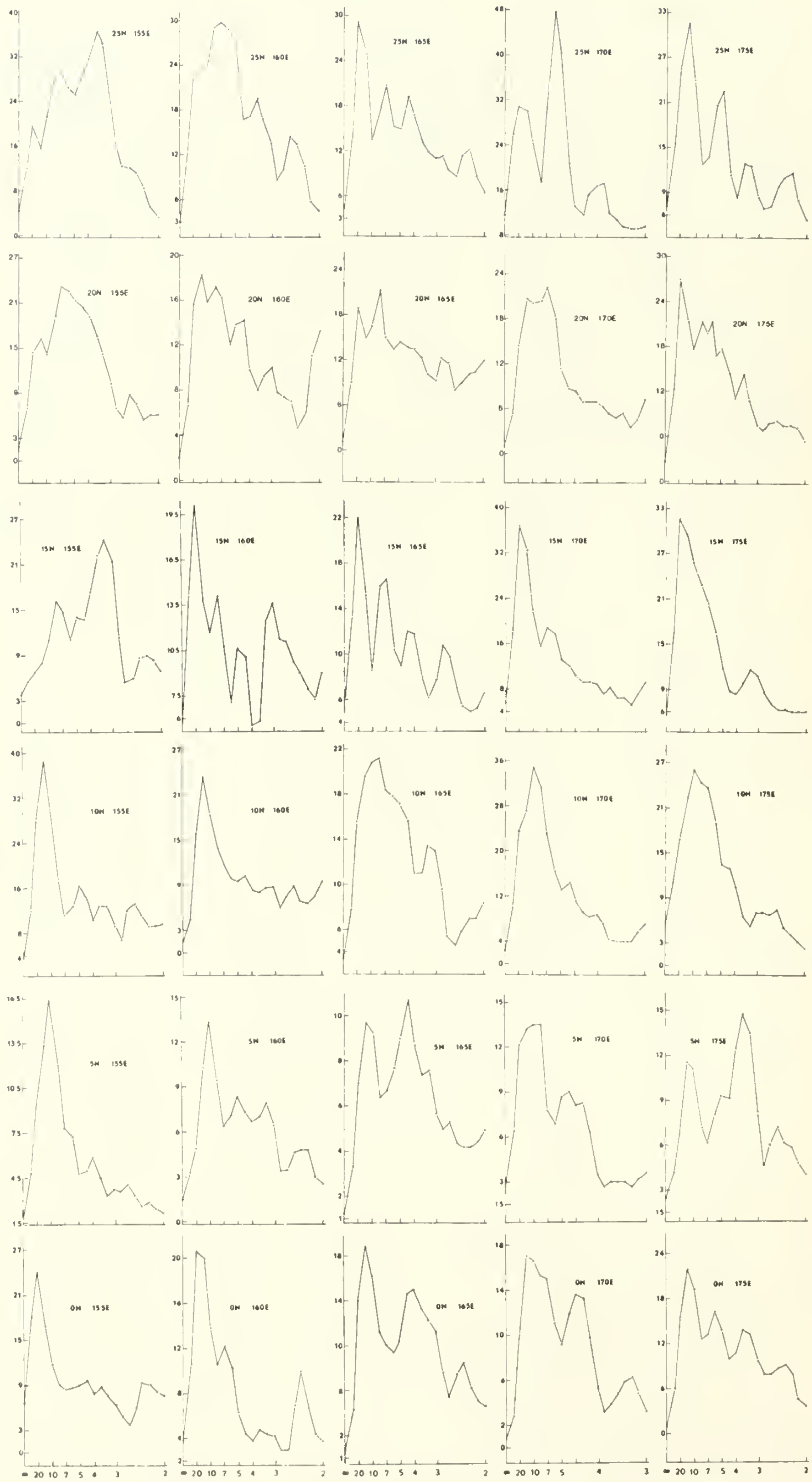

Fig. 3. (continued)

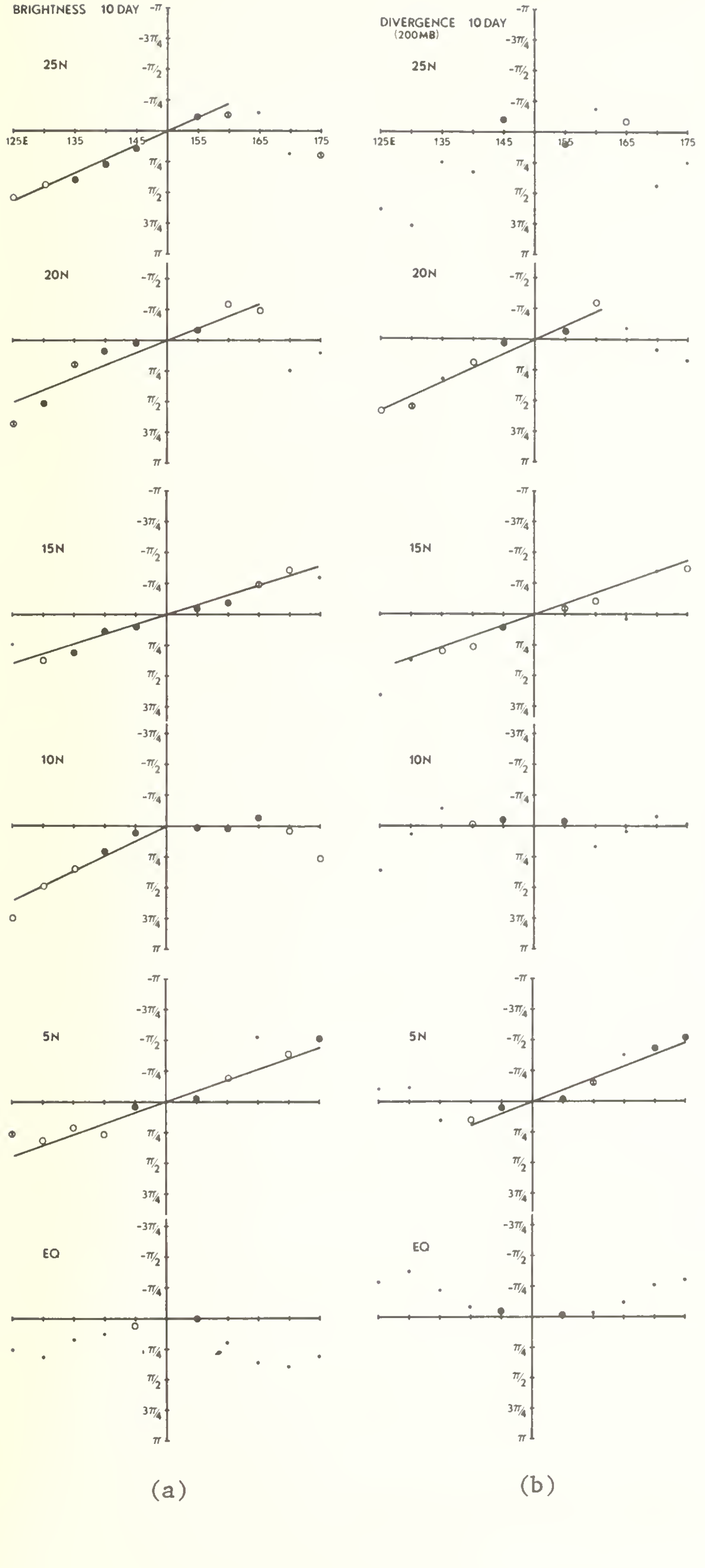

Fig. 4. Interlongitude cross-spectra of (a) brightness and (b) divergence for the 10-day band. The abscissa is longitude of the series that is crossed with the base series (150E); the ordinate is phase difference with positive values indicating that the base series leads the other series. Plotting symbols indicate the significant level of coherence square associated with each phase difference in the following way: Blackened circles, ≥ 99%; circles with a cross in it, 95-98%; open circles, 90-94%; small dots, < 90%.

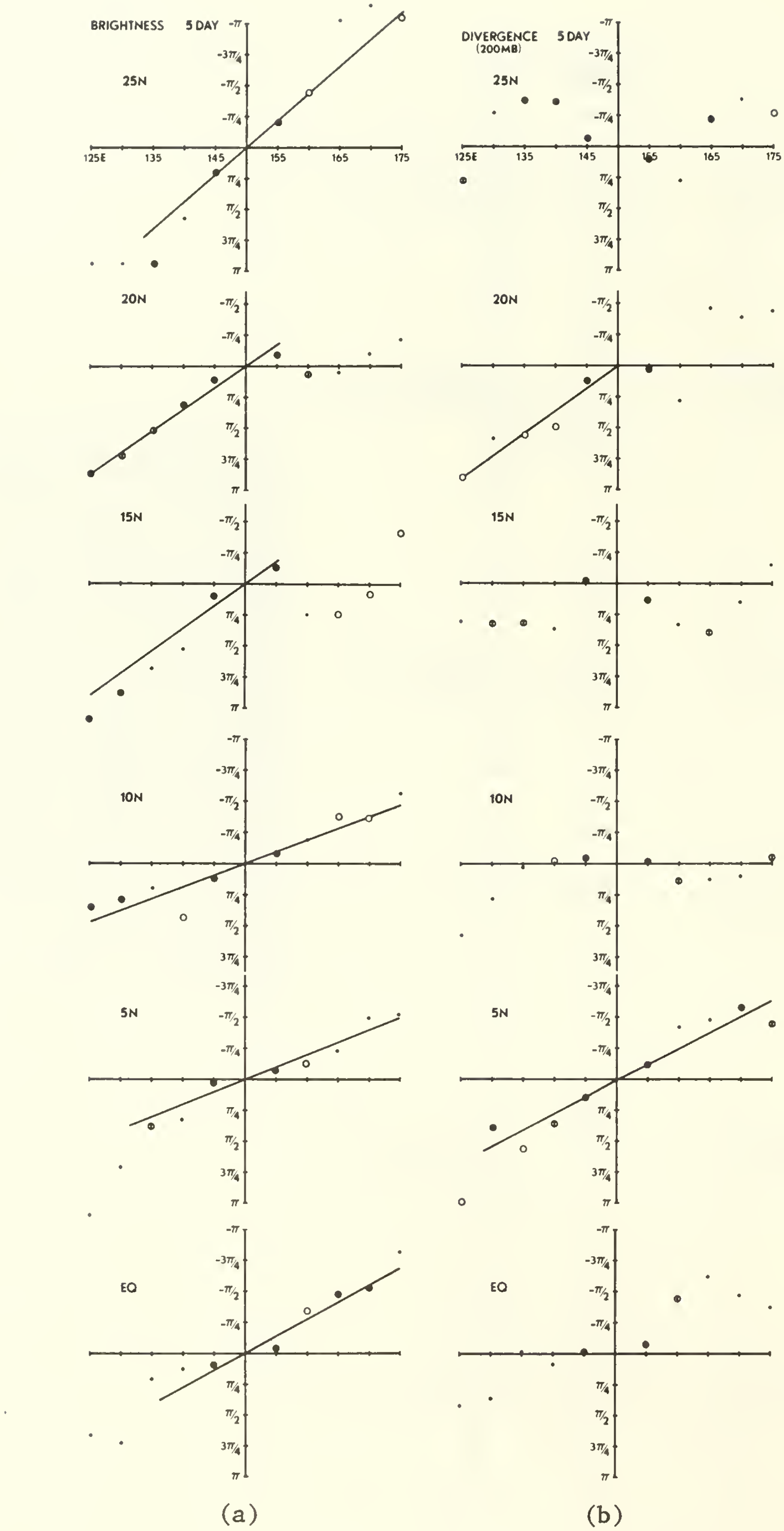

Fig. 5. Same as Fig. 4 except for the 5-day band.

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